

THE PERFORMANCE OF ADVANCED SOLAR CELLS FOR INTERPLANETARY MISSIONS

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ABSTRACT

Recent advances in space solar cell technology have produced substantial increases in Air Mass Zero (AM0) efficiency. Since these cells have been developed primarily for Earth orbiting missions, little is known of their behavior at distances far from the sun. In order to better define the photovoltaic performance of arrays for deep space missions, JPL has completed initial measurements on a number of advanced cells under a variety of LILT (low intensity, low temperature) conditions. These include high efficiency silicon, and multi-junction III-V devices. The test results show that multijunction cells suffer from LILT degradation and that at 5AU (approximately the solar distance of Jupiter), efficiency advantages over high efficiency silicon are minimal. Silicon cells optimized for 3-6 AU operation not only equal the efficiency available from 2 and 3 junction cells, but also tend to be more uniform.

INTRODUCTION

During the past decade, there has been dramatic progress in the development and production of high efficiency space solar cells. In fact, test efficiencies (Air Mass Zero, 28C), have seen efficiencies rise by more than 50%, from the 1990 production silicon cell to the 2000 production multijunction solar cell. These cells have had a major impact on Earth orbiting spacecraft. The Jet Propulsion Laboratory has utilized photovoltaic solar cells on a wide range of interplanetary missions, from Mercury flybys to Mars missions and more recently for a comet flyby (Stardust). Due to the inverse square fall off of solar intensity with solar distance, it is necessary to fabricate relatively large power systems in order to achieve modest power output at far sun distances. In order to extend the range of photovoltaics to encompass missions well beyond the distance of Mars, low system mass is needed. Higher cell efficiencies are key to accomplishing this. Consequently, the new cell developments are of great interest to JPL. However, the advanced cells have been developed for Earth orbit applications, and their far sun performance are unknown. For this reason, JPL began an investigation of advanced solar cells under LILT conditions.

This effort represents a continuation of work that JPL has undertaken for many years in support of its Interplanetary mission [1]. To this end, JPL obtained a variety of cells from manufacturers for preliminary LILT testing. The range of interest corresponds to use between 1 AU and 5 AU. High efficiency cells were obtained from ASE, Sharp, and Sunpower and advanced III-V devices from Emcore, Spectrolab, and Tecstar. In support of this effort cell testing was done at JPL, GRC, and Spectrolab. In most cases, more than one test facility was used to test each manufacturer's cells, with the exception of Spectrolab, where testing was performed on their cells only. All cells were commercially available designs and most were optimized for 1 AU use. The exception to this were silicon cells from ASE which were optimized for use at 3 - 5 AU. It was expected that this would give these cells an advantage over the other silicon cells, but it was felt useful to quantify the magnitude of the advantage that could be obtained by cell optimization. Expectations were high for the multijunction cells since the AM0 values were significantly better than silicon. Even though the multijunction cells have smaller temperature coefficients than silicon, rough extrapolation from AM0, 28C values suggested the possibility of achieving 30% at 5 AU. Although earlier studies had shown limits in the multijunction cell performance under LILT [2], there was optimism that the recent improvements in the cells might lead to improved LILT behavior.

CELL TEST FACILITIES

NASA Glenn

The LILT conditions were achieved with a temperature controlled plate illuminated with a Spectrolab X-25 solar simulator. The test cells were vacuum chucked to a brass plate, whose temperature was varied with resistive heaters and circulating liquid nitrogen, and monitored with a single embedded thermocouple. The test plate was in a closed environment with a quartz window and constant nitrogen gas purge. Actual cell temperatures were measured through the use of thermocouples mounted on the surface of witness cells. Cell temperature was measured at the beginning and end of each I-V curve;

contacts to the cells was made using standard four-wire techniques. The proper illumination for one AM0 sun was achieved by adjusting the simulator lamp intensity to the correct short-circuit current for a calibrated cell on the test plate at 25 °C. The light level was decreased by using a set of metal screens, which changed the light level without altering the spectrum. These facilities were used in previous work reported by them [2].

Spectrolab

Spectrolab used an X-25 simulator which included a filtering attachment for close spectral matching at the cell test plane. Solar cells were tested in a vacuum chamber to prevent frosting. All cells were hard mounted to a brass substrate using DC1150 adhesive. The test plate temperature was monitored using a thermocouple attached to the plate. The temperature differential between the cell surface and the block was measured for one cell and applied for all test samples. JPL balloon traceable standards were used to set up the simulator. The procedure accounted for the optical impact of the quartz window through which the simulator beam passed to illuminate the test cells. Screens were used to adjust the light intensity to levels below AM0.

JPL

JPL tested using an X-25 simulator which included additional filtering to better match the AM0 spectrum. Similar to the Spectrolab setup, test samples were hard wired and bonded to a brass test plate and placed inside a vacuum chamber. All electrical connections were of the four point configuration. Balloon reference cells were used to set up the simulator and beam intensity at the test plate was adjusted using wire screens.

RESULTS

Solar cells were measured over a range of

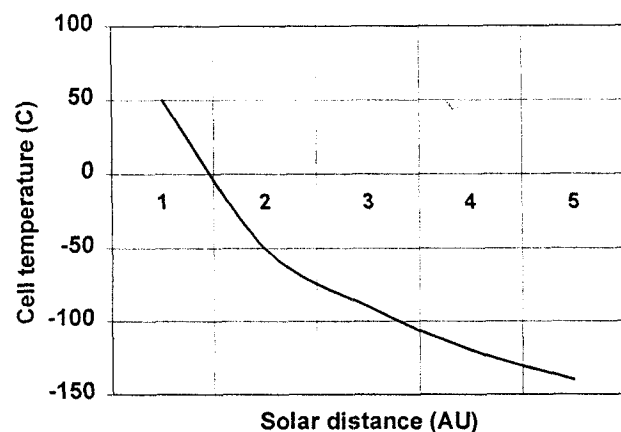


Figure 1. Cell Temperature vs. Solar Distance

temperatures and intensities that covered operation from 1 AU to approximately 5 AU solar distance. Figure 1 presents temperature as a function of solar distance. Actual cell temperature can vary from this through changes in array

absorptivity and emissivity, but generally follow the figure 1 curve. Although there are a number of ways to present the data, such as cell characteristics as a function of temperature for various solar intensities, the data shown here extracts the characteristics as a function of AU. This does provide some reduction in data, but clearly exhibits the relationship to solar distance. In addition, rather than show curves for each manufacturer's cells, it was felt, after reviewing the data, that it made more sense to present typical data for each cell type. This is done for two reasons. First, the data for each cell type were remarkably similar, regardless of manufacturer. Second, since these cells were not designed for LILT applications, and since the quantities were relatively small, any differences would not be statistically significant and suggesting that there was a "better" manufacturer would be misleading.

Figure 2 shows the cell efficiency as a function of AU. Two things stand out here. First is the fall off in

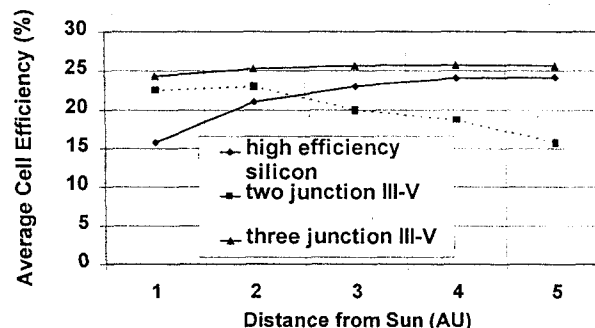


Figure 2. Average Solar Cell Efficiency vs. Solar Distance

efficiency for the two junction device after about 2 AU, and the second is the closeness in efficiency between silicon and three junction devices at 5 AU. This results from the differences in cell temperature coefficients (silicon having a greater rate of increase for efficiency), but also from a flattening in the three junction cell data between 3 and 4 AU. A third factor, one that does not show in this data, is the much greater spread in data with increasing solar range for multijunction devices. In general, all cell groups had standard deviations in efficiency at 1 AU of approximately 2%. For silicon cells at 5 AU, this increased to about 5%. For multijunction cells the deviation at 5 AU was 10% or, in the case of two junction cells, even greater. Oddly enough, the highest measured cell at 5 AU was a two junction device at nearly 27%. So the poorer performance of multijunction cells reflects the occurrence of some cells with very low output. As a comment, it is noted that the best performing silicon cells at 5 AU were the ASE devices which ran about one efficiency point higher than the other silicon devices. This was directly due to their specific LILT application design features. They also exhibited notably lower efficiency at 1 AU for the same reason. Due to the benefits of their LILT design, they were not included in the data curves featured here, but do illustrate that LILT performance can benefit from device modification.

Figure 3 displays the behavior of cell voltage as a function of solar distance. It is important to recognize that the cell efficiency enhancements that occur with increasing solar distance are the result primarily of increases in cell voltage. That if the spacecraft power system can not accommodate the voltage increase, cell efficiency increases will not be realized. All cell types exhibit an increase in cell voltage, although multijunction cells appear to flatten out between 4 and 5 AU compared to silicon. The percent

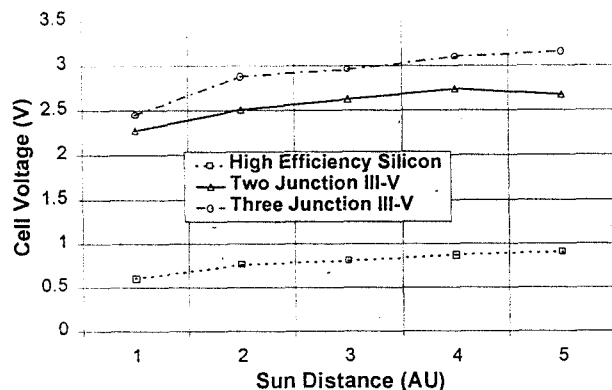


Figure 3. Cell Open Circuit Voltage vs. Solar Distance

voltage increase for silicon is much greater than for the multijunction cells, implying that silicon array voltages would show much higher change in operation from 1 AU to 5 AU. The voltage increase for silicon over this range is 50%, compared to 17% and 26% for two and three junction cells, respectively. The rapid fall off in efficiency seen in the previous figure for two junction cells is not reflected in the open circuit data.

The cell characteristic that does reflect the efficiency performances is the cell fill factor. This is shown in figure 4. In this figure the strong increase in fill factor for

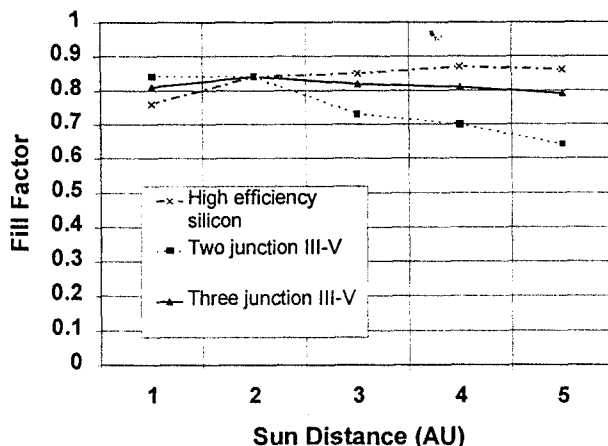


Figure 4. Cell Fill Factor vs. Sun Distance

silicon is evident. Three junction cells show an increase to a distance of 2AU, and then a slight roll off with increasing solar distance. In contrast, the two junction cells are relatively flat between 1 and 2AU, and then fall off significantly with increasing solar distance. As with the efficiency data, this behavior was not shown by all cells within the group, but reflects the contribution from some cells that had very dramatic fill factor degradation. Other cells actually maintained high fill factors at high solar distances.

CONCLUSION

The sections above describe the results of LILT measurements on the most recent state-of-the-art commercially available high efficiency space solar cells. These cells have all been space qualified and in many cases, have been used to power spacecraft with great success. They represent significant improvements in efficiency over cells used 5-10 years ago. What is clear from the above results is that improved cells developed for Earth orbiting missions do not always translate into similar improvements when used in a different environment, such as missions much more distant from the sun. These results are not intended to set quantitative limits on cell performances for missions far from the sun, but are intended to indicate qualitatively, the general performance of commercially available cells. These results show a remarkable similarity in cell performance at a distance of 5 AU. Although the lower temperature coefficients of the III-V cells indicated that their advantage over silicon at 1 AU would be reduced at 5 AU, it is clear that other factors are reducing the III-V cell performance. Selection of a cell for such an application will depend on a number of additional factors including the power profile required over an entire mission, the radiation environment, and array mass and area, for example. Is the power required primarily at the 5 AU distance (i.e., Jupiter) or is there an additional use near Earth for high power to support electric propulsion?

These results do suggest that developing cells for the LILT conditions may lead to better performance. The cell data showed high deviation in performance for cells at 5 AU whereas the same cells had very close performance at 1 AU. Isolating the difference in cells between high performers and low performers might enable manufacturers to make process adjustments that would eliminate the poorer performers at 5 AU. Obviously, a funding source for such work would be needed since LILT behavior has negligible impact on the major commercial uses of these devices. Inasmuch as not all cells of a particular type or manufacturer show severe LILT degradation, it is felt that LILT optimization, such as shown for the ASE silicon cells, could increase performance at 5 AU, even at the loss of some 1 AU performance.

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